Physica Scripta. Vol. T80, 310–311, 1999

Laboratory Measurements of Resonant Contributions to Fe XXIV Line Emission

M. F. Gu,[1] P. Beiersdorfer,[2] G. V. Brown,[2] S. M. Kahn,[1] D. A. Liedahl,[2] K. J. Reed[2] and D. W. Savin[1]

[1] Department of Physics and Columbia Astrophysics Laboratory, Columbia University, New York, NY 10027, USA
[2] Lawrence Livermore National Laboratory, Livermore, CA 94550, USA

Received September 13, 1998; accepted November 16, 1998

PACS Ref: 34.80.Kw, 34.80.Lx

Abstract

Using an electron beam ion trap, we have measured the relative cross sections for Fe XXIV line emission at electron energies between 0.7 and 3.0 keV. Good agreements with distorted wave and R-matrix calculations are found at energies above 1.5 keV. At lower energies, the contributions of resonant excitation are observed and agree with R-matrix calculations. Below the excitation thresholds, the intensities of dielectronic recombination satellites for capture into $n \geq 5$ levels are measured.

1. Introduction

We have measured $n = 3 \rightarrow n = 2$ line emission of Fe XXIV at electron energies between ~0.7 and 3.0 keV. Here we present the relative cross sections for producing Fe XXIV line emission at $\lambda = 11.18$Å, $\lambda = 10.62$Å, and $\lambda = 10.66$Å and the associated Fe XXIII satellite lines produced by dielectronic recombination (DR) which blend with these features.

Various processes contribute to the line emission observed from a collisionally ionized plasma. Direct excitation (DE) is the most important one at energies above the threshold. Resonant excitation (RE) can populate the same levels as DE via dielectronic capture followed by autoionization to the level of interest. Below the threshold, DR onto Fe XXIV produces high n satellites which cannot be resolved from the Li-like lines.

In this work, we have observed the following processes:

DE

$$\mathrm{Fe}^{23+}(2\mathrm{s}) + \mathrm{e}^- \rightarrow \mathrm{Fe}^{23+}(3\mathrm{l}) + \mathrm{e}^- \rightarrow \mathrm{Fe}^{23+}(2\mathrm{l}') + \mathrm{h}\nu_1 + \mathrm{e}^-$$

RE

$$\mathrm{Fe}^{23+}(2\mathrm{s}) + \mathrm{e}^- \rightarrow \mathrm{Fe}^{22+}(4\mathrm{l}'\mathrm{nl}'') \rightarrow \mathrm{Fe}^{23+}(3\mathrm{l}) + \mathrm{e}^- \rightarrow \mathrm{Fe}^{23+}(2\mathrm{l}''') + \mathrm{h}\nu_1 + \mathrm{e}^-$$

DR

$$\mathrm{Fe}^{23+}(2\mathrm{s}) + \mathrm{e}^- \rightarrow \mathrm{Fe}^{22+}(3\mathrm{lnl}') \rightarrow \mathrm{Fe}^{22+}(2\mathrm{l}''\mathrm{nl}') + \mathrm{h}\nu_2 + \mathrm{e}^-$$

with l = p and d. Quantum mechanically, there is no way to distinguish between DE and RE, and we measure the coherent sum of the two processes. DR satellites with $n \geq 5$ are not resolved spectroscopically from the corresponding Li-like lines. Their contributions are separated using the fact that they occur at electron energies below the EIE (electron impact excitation) thresholds.

2. Experimental Technique

EBIT [1] uses a magnetically confined electron beam to produce a potential well which traps the ions in the radial direction. In the axial direction, ions are trapped by voltages applied to the top and bottom drift tubes. The electron beam is also used to ionize and excite the trapped ions. Radiative decay of the excited ions results in X-ray emission which is observed by flat crystal spectrometers (FCS) [2] through the X-ray ports.

We collect data as the beam energy is linearly swept between ~0.7 and 3.0 keV using an event-mode data acquisition system [3]. During the sweeping of the beam energy, the charge balance changes insignificantly because the sweep period is chosen to be much smaller than the ionization and recombination time scales at these energies. By varying the anode voltage of the electron gun synchronously with the beam energy, we maintain a constant electron density and beam-ion overlap. The measured line intensities as a function of beam energy therefore may be used to derive the excitation cross sections by normalizing the results to theory. In this work, we use R-matrix [4] calculations of the $2s_{1/2}$–$3d_{5/2}$ cross section at energies between 2 and 3 keV as our normalization. In this energy range, cascades from higher levels contribute to the observed line emission. The contributions from $n \leq 7$ levels are included using the *Hebrew University Lawrence Livermore Atomic Code* (HULLAC) [5] calculations. The $3d_{5/2} \rightarrow 2p_{3/2}$ transition blends with the $3d_{3/2} \rightarrow 2p_{3/2}$. The predicted 10% contribution from $3d_{3/2} \rightarrow 2p_{3/2}$ has been subtracted out. The $3p_{3/2} \rightarrow 2s_{1/2}$ and $3p_{1/2} \rightarrow 2s_{1/2}$ transition have higher photon energies than $3d_{5/2} \rightarrow 2p_{3/2}$, and the transmittances of the spectrometer and detector windows are higher. These effects are accounted for as described in Ref. [6].

3. Results

Figure 1 shows the normalized cross sections for producing the $3p_{3/2} \rightarrow 2s_{1/2}$, $3p_{1/2} \rightarrow 2s_{1/2}$ and $3d_{5/2} \rightarrow 2p_{3/2}$ line emission. The error bars on the data points show the 1σ statistical uncertainties. Note that additional ~6-8% uncertainties due to the normalization may shift the various curves without changing their shape. The $3l5l'$ and $3l6l'$ DR resonances are well separated. All other DR resonances between ~1.0 keV and the thresholds are unresolved and appear as a continuous increase in the cross sections. The RE feature at ~1.25 keV is produced by dielectronic capture into the $4l5l'$ level followed by autoionization to the $3p_{3/2}$,

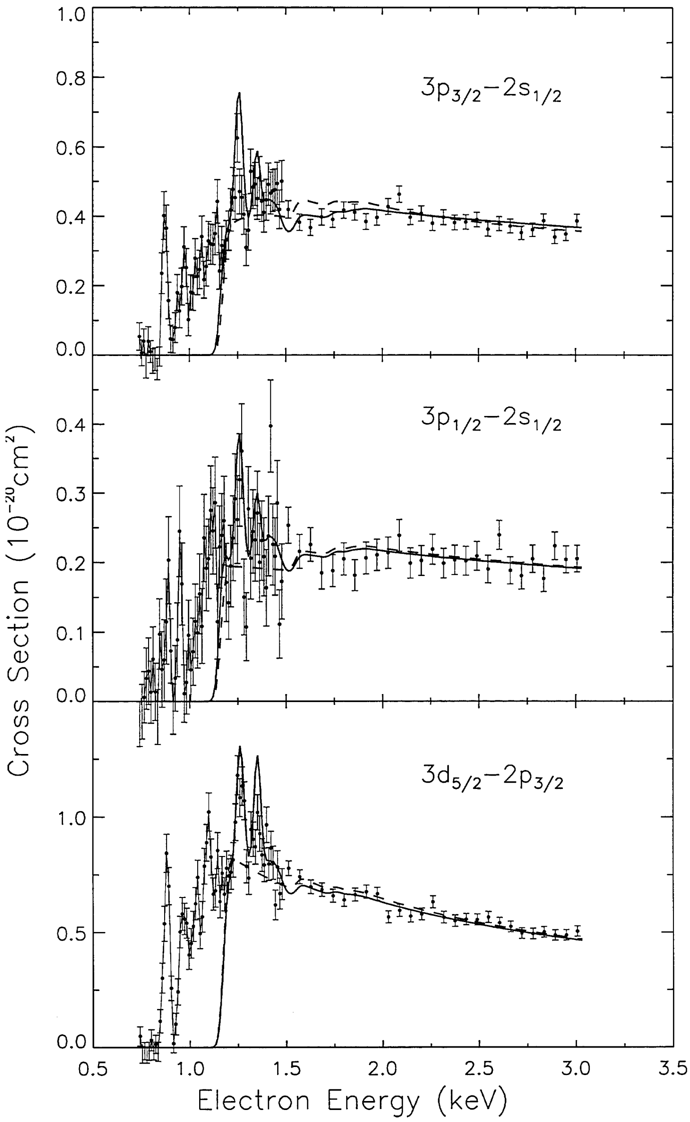

Fig. 1. Normalized cross sections for producing Fe XXIV line emission. The solid lines are the R-matrix calculations of DE and RE [4] plus HULLAC calculations for cascade contributions. The dashed lines are HULLAC calculations. Below the thresholds, the line emission is due to DR satellites for captured electrons in the $n \geq 5$ Rydberg levels. The data points at energies above ~1.5 keV have been rebinned to have an ~55 eV bin size for clarity. Those below ~1.5 keV have an ~11 eV bin size.

$3p_{1/2}$, or $3d_{5/2}$ levels of Fe XXIV. The feature at ~1.35 keV is associated with the dielectronic capture into $4l6l'$. The theoretical calculations shown in Fig. 1 include cascades for $n \leq 7$ using HULLAC data. The beam energy spread is nearly Gaussian [7]. The FWHM is determined by fitting the $3l5l'$ DR peak and a value of 45 eV is found. The theoretical curves have been convolved with the beam energy distribution.

We find excellent agreement between the R-matrix and distorted wave HULLAC cross sections and our measurements, except at energies near threshold where the HULLAC calculations do not account for RE contributions. Integrating our results with a Maxwellian electron energy distribution, we find that at temperatures where the Fe XXIV abundance peaks in collisionally ionized plasmas, RE contributes ~5% to the total line emission.

The $n \geq 5$ DR satellites contribute ~10% to the total Fe XXIV line emission at temperatures where the ion is abundant in collisionally ionized plasmas. The $n = 3$ and 4 satellites are expected to have larger cross sections and total contributions from all DR satellites may be as large as ~20%.

4. Conclusions

We have measured the relative cross sections for producing Fe XXIV, and transitions at the electron energies between ~0.7 and 3.0 keV. Good agreement is found with R-matrix and distorted wave calculations At temperatures where Fe XXIV is abundant in collisionally ionized plasmas, RE contributes ~5% and the $n \geq 5$ DR satellites contribute ~10% to the total line emission. Including the DR satellites for $n = 3$ and 4, these contributions are non-negligible. In situations where the ionization balance is not determined by the kinetic temperature of plasmas, RE and DR satellites may dominate the line emission.

Acknowledgements

The authors wish to thank S. T. Manson for stimulating conversations and P. A. D'Antonio, E. W. Magee, and D. H. Nelson for their expert technical support. Work at Lawrence Livermore National Laboratory was performed under the auspices of the US Department of Energy under contract No. W-7405-ENG-48. This program is supported by a NASA High Energy Astrophysics X-Ray Astronomy Research and Analysis grant NAGW-4185 (Columbia University) and work order W-19127 (LLNL).

References

1. Levine, M. A., Marrs, R. E. Henderson, J. R., Knapp, D. A. and Schneider, M. B., Physica Scripta. **T22**, 157 1988.
2. Beiersdorfer, P. and Wargelin, B. J., Rev. Sci. Instrum. **65**, 13 1994.
3. Knapp, D. A., Marrs, R. E., Schneider, M. B., Chen, M. H. and Levine, M. A., Phys. Rev. A **47**, 2039 1993.
4. Berrington, K. A. and Tully, J. A., Astron. Astrophys. Suppl. Ser. **126**, 105 1997.
5. Bar-shalom, A., Klapisch, M. and Oreg, J., Phys. Rev. A **38**, 1773 1988.
6. Savin, D. W. *et al.,* Astrophys. J. Lett. **470**, L73 1996.
7. Beiersdorfer, P. *et al.*, Phys. Rev. A **46**, 3812 1992.